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An Innovative Approach to Non-Contact Cleaning of Mini-Ball Bearings

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Abstract. The bearing industry represents a critical segment of the modern economy, directly influencing the operational reliability and service life of various machines, equipment, and components employed in high-responsibility sectors of mechanical engineering and transportation infrastructure. Despite ongoing advancements and technological improvements in rolling bearing manufacturing, there remains a significant risk of residual contamination by particulates of various origins, primarily during production. This problem becomes particularly relevant in the case of miniature rolling bearings, characterized by an outer diameter of less than 30 mm. Conventional cleaning techniques currently applied in industrial practice often demonstrate limited efficiency in removing microcontaminants from hard-to-access zones within non-separable bearing assemblies. This study proposed an innovative non-contact cleaning method based on comprehensive investigations. The technique integrates the synergistic effects of pulsed alternating magnetic fields and ultrasonic excitation, offering enhanced cleaning performance without compromising the structural integrity of precision components. The results of the granulometric composition of the removed contaminant particles of ball bearings by different methods were presented. The optimum angles of bearing inclination were experimentally evaluated at various locations of ultrasonic wave radiation sources and the action of a pulsed magnetic field. The effectiveness of the developed combined method on aircraft ball bearings demonstrated its advantages in removing both large and small contaminants, confirmed by vibration diagnostics and microscopic analysis. Testing of the method at leading aircraft manufacturers underlines the practical significance of the developed approach and has the potential to significantly improve the quality, service life, and reliability of precision parts and mechanisms. Depending on the contamination degree and the bearing type, the cleaning time ranged from several seconds to 2–3 minutes, allowing the developed combined method to be integrated into the manufacturing technological cycle of rolling bearings using the necessary automated systems and equipment as the final cleaning operation. This ensures the principle of improving the innovation of production. Using ultrasonic waves allowed for the removal of the strongest films of complex structure. Overall, combining ultrasound with a pulsed magnetic turbulent cleaning method significantly increased the effectiveness of the cleaning process.

Keywords: miniature ball bearings, precision parts, microscale contamination control, non-contact ultrasonic cleaning, tilt-angle control, pulsed magnetic turbulent cleaning method, process innovations.

1 Introduction

Due to their compact size, high manufacturing accuracy, low friction, and ability to operate at high rotational speeds, mini-ball bearings cover various components in aviation, other defense equipment, medicine, and instrumentation. The cleanliness of the working surfaces of such bearings is a critical factor in ensuring their reliable and durable operation in various high-tech industries [1].

Despite thoroughly cleaning both used and new bearings using existing cleaning methods [2], there is always a risk of residual microscopic contamination. Such contaminants are invisible to the human eye, but can cause damage to raceways, balls, or cages. These microscopic damages affect the operation of the bearings during further use and shorten the service life of not only the bearing units, but also the associated machinery and equipment. This can lead to serious consequences and premature failure of such machines in critical situations. Therefore, finishing operations for cleaning rolling bearings are essential components of the technological process of manufacturing and repairing such bearings, which contributes to the development and implementation of innovations in the bearing industry and the reduction of CO_2 emissions [3] by reducing various energy costs. Carbon dioxide emissions have an impact on climate change.

Technological innovations (e.g., modern integrated approaches to ensuring high quality in manufacturing mini-ball bearings) include strict control and continuous process improvement at all stages of production. However, insufficient attention is paid to the cleaning issues from various contaminants, including during manufacturing. This is primarily due to the lack of effective cleaning methods integrated into multi-series or mass production, such as the finishing operations for rolling bearings.

Therefore, developing and integrating innovative solutions such as highly efficient automated cleaning and cleanliness control systems into production is an actual task in designing and modernizing production facilities. This approach is essential for industries where the reliability and durability of ball bearings directly affect the safety and efficiency of critical mechanical systems and complex equipment.

2 Literature Review

Analytical studies performed by analyzing special scientific literature and patents indicate the need to ensure the cleanliness of the surfaces of precision tribunal parts at all stages of the technological process of their manufacture, assembly, and operation [4, 5]. It is crucial to consider the peculiarities of assembly operations and the degree of production automation [6]. It is also advisable to consider the type of processing and cutting modes. The final accuracy of the product depends on the correct selection of cutting modes. The circular pitch error accumulated in previous operations under the influence of feed and depth of cut is difficult to eliminate with finishing operations [7].

Not only machining accuracy, but also the accumulation of residual micro metal on the working surfaces of parts, which is a secondary cutting product, depends on properly selected cutting modes. Therefore, an essential stage in implementing scientific solutions into industrial practice involves laboratory investigations of precision tribosystems and lubrication systems throughout all design and production phases [8, 9]. Ultrasonic abrasive removal of various microburrs is often used as a finishing operation for machining precision surfaces [10].

Concerning rolling bearings, the primary published studies relate to diagnostics. The research work [11] presented a hybrid method of vibration diagnostics, which uses traditional and empirical approaches to determine informative frequency components, allowing for the assessment of the performance of various types of bearing rollers with high reliability.

Other researchers have also adhered to the principle of assessing the performance of rolling bearings by vibration characteristics [12]. Information about the malfunction is contained in the vibration signal, which reflects the corresponding defects.

Simultaneously, considerable attention is paid to filtering and processing other vibration and noise signals emitted by the rest of the components of the diagnosed machine. The decomposition of noise and vibration by the minimum entropy deconvolution is widely used in diagnosing rolling bearings [13]. Methods for studying the performance and defects of rolling bearings are constantly being optimized [14].

An essential stage in this process is the development of degradation indicators that should be included in models for assessing bearing performance [15]. Using vibration models, many different vibration equipment and machines have been built, according to the principle of operation [16, 17].

Frequency demodulation is widely used for bearing diagnostics [18], and the accuracy of fault identification is increased using special methods and equipment based on a modified particle swarm optimization algorithm [19].

A research team [20] has been investigating the influence of contamination in rolling element bearings by particles smaller than 5 μm on their performance. These particles, when introduced into the contact zone of friction surfaces together with the lubricant, contribute to the formation of surface and subsurface damage under the influence of electric currents. Such damage adversely affects the operational reliability of the bearings. Therefore, diagnostics [21] plays a crucial role in assessing the performance condition of rolling bearings. However, preventing many failures depends on the timely cleaning of precision tribosystems.

Ultrasonic cleaning methods are most commonly used in industry but have specific applications. After machining and assembly, ultrasonic cleaning of precision surfaces of parts is a regular practice in many modern industries [22]. In this case, cleaning is performed due to the cavitation effect [23]. Tribocavitation is distinguished as a specific form of cavitation [8, 9]. These are the so-called non-contact methods, which include the pulsed magnetic turbulent method [2]. Most of the methods of non-contact cleaning of rolling bearings published in international practice are covered in patents for inventions. It is known that the objects of intellectual property are highly efficient devices for cleaning a ball bearing belt, a machine, and an ultrasonic bearing cleaning device.

Attention is also paid to methods of maintenance of bearings, bushings, connecting pins, and chains.

Compositions and methods for washing bearings have also been patented. Much attention is paid to the development of bearing cleaning equipment in China and to the fundamental theories of ultrasonic cleaning at the level of the US National Aeronautics and Space Administration (NASA) [24].

A literature review reveals many unresolved challenges related to ensuring the required reliability and service life of high-precision rolling bearings, particularly miniature ones, due to the critical importance of maintaining sufficient cleanliness. Despite strict quality control measures during the manufacturing of rolling bearings, a significant amount of metallic and non-metallic contaminants is still found even in newly produced bearings. These contaminants contribute to accelerated wear of the contacting surfaces from the onset of operation.

The studies [20, 21] address this issue primarily from a theoretical standpoint, while the available cleaning methods either effectively break the bonds between contaminants and bearing surfaces such as ultrasonic techniques but lack efficiency in removing the detached pollutants from within the bearing [24], or they facilitate contaminant removal through turbulent flow, yet insufficiently disrupt the adhesion of particles to critical surfaces [2]. Many of these methods cannot be integrated into the industrial production process.

Based on the analysis conducted, the authors have developed a novel method, fundamentally different from existing approaches, which combines effective disruption of contaminant adhesion with efficient removal from the bearing interior. The proposed method is designed for implementation according to international technology transfer standards [25] and can be integrated into the manufacturing workflow of miniature rolling bearings.

3 Research Methodology

Laboratory studies show that turbulent flows and cavitation are formed during the cleaning of rolling bearings by non-contact methods. Notably, the following factors affect the efficiency of cleaning by ultrasonic methods:

– the direction of propagation of ultrasonic waves (upward from the bottom or from the sides);

– the angle of ultrasonic wave incidence on the bearing surface;

– access of the cleaning fluid to the internal gaps between the rolling elements, the housings, and the separator.

In addition, the quality of rolling bearing cleaning is affected by their placement in the cleaning device. For example, if the bearing is located at the bottom of the bath, standing waves can form during the cleaning process, where vibrations are weaker. Therefore, cavitation is reduced in these areas, and the beneficial effect decreases. Observation of the cleaning process at the bottom of the bearing, parallel to the bottom of the bath, showed poor washing of such a bearing with the cleaning fluid. This can lead to the accumulation of dirt, especially inside the raceways.

This results in an uneven distribution of cavitation, which is associated with the main effect of the field source in the center of the liquid volume. Therefore, the bearings on the bottom of the bath were not cleaned well: the upper and side surfaces were cleaned well, but the lower and inner surfaces were much worse. The ultrasonic bath was modernized to ensure high-quality cleaning of the studied mini-ball bearings, and an appropriate research method was developed. The essence of the methodology is to place the bearings to be cleaned at the proper angles, which were determined experimentally. For this purpose, special mandrel-holders were manufactured, with the possibility of adjustment, to determine the effective angle of inclination (Figure 1).

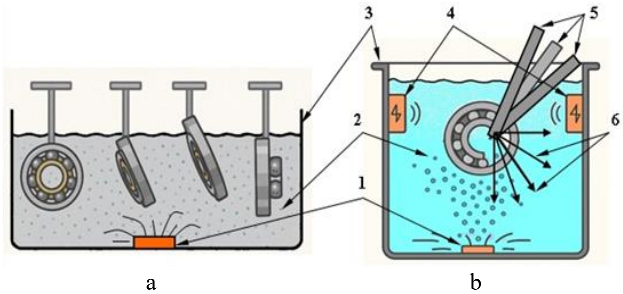


Figure 1 – Ultrasonic baths: a – standard with bottom transducer; b – modernized with bottom and side transducers (1 – bottom transducer; 2 – cavitation in the cleaning liquid; 3 – bath; 4 – side transducers; 5 – bearing position adjustment mechanism; 6 – possible angles of inclination to the bottom and the side walls of the bath)

According to previously obtained results by the authors [2], the cleaning time was up to 20 seconds for new bearings and 2–3 minutes for miniature bearings that had been in service and were heavily contaminated. The installation angle was determined experimentally. The frequency and positioning of the ultrasonic emitters were also established experimentally.

The working fluid was filtered after the cleaning procedure, and the filtered contaminants were weighed and subjected to quantitative analysis using a scanning electron microscope. The efficiency of the proposed method was evaluated based on the total mass of removed contaminants and the ability of the applied ultrasonic waves and electromagnetic fields to penetrate the most inaccessible (shadowed) areas of the bearing. Experimental studies were carried out on the cleaning of bearings with inclination angles (15°, 30°, 45°, 60°, and 90°) in standard (Figure 1 a) and modernized (Figure 1 b) ultrasonic baths.

According to the results of comparative experiments, the cleaning efficiency of the studied miniature ball bearings placed at the selected angles in a classic bath can be shown as follows:

– ≤ 15° is not highly effective, since a significant part of the bearing surface is parallel to the bottom of the bath, which limits the access of ultrasonic waves;

– 30° to 45° is more effective, as it provides better access of the ultrasonic waves to all bearing surfaces, and the cavitation bubbles generated by the ultrasound are more effective in removing contaminants;

– 60° angle, which can be effective in some cases, but there is no significant improvement in cleaning compared to the angles of inclination from 30° to 45°;

– 90° sharply reduces the efficiency since most of the waves pass by the axial plane of the bearing under investigation.

In general, 30° to 45° tilt angles are quite effective when cleaning with a bottom-mounted ultrasonic transducer. They provide the most optimal access to ultrasonic waves in all working areas and surfaces of the bearing. However, the specific design of the miniature bearing, its size, and the type of contamination must be considered.

The modernization of the ultrasonic bath has led to a change in the distribution of ultrasonic waves (Figure 1 b). The location of the emitters on the side walls of the bath, rather than on the bottom, significantly changes the effect of the bearing's angle of inclination on its cleaning efficiency. Instead of a direct impact from the bottom up, the ultrasonic waves propagate horizontally, perpendicular to the side walls of the bath on which the emitters are located.

The bottom positioning of the transducers often results in the formation of more pronounced standing waves vertically, with alternating zones of high and low intensity. When ultrasonic emitters are placed laterally, standing ultrasonic waves will be formed mainly in the horizontal plane. Therefore, such an arrangement can contribute to a more even distribution of the ultrasonically induced cleaning energy over the height of the bath. This is observed if the emitters are located symmetrically on opposite walls. The research results show that ultrasonic waves, which in experimental conditions must repeatedly reflect from the side walls and bottom of the bath, create a very complex pattern of energy distribution, which leads to the appearance of zones with lower intensity of cleaning energy in the center and corners of the bath.

Studies of the quality of cleaning of rolling bearings placed at selected angles in the modernized bath showed the following results:

– at an angle of placement of 15°, the axial surfaces of the bearing receive the most intense action, but its upper part is more shielded and is cleaned less efficiently due to reflected ultrasonic waves and less direct exposure;

– 30° to 45° provides a more balanced effect on all bearing working surfaces. Various parts of the bearing are alternately exposed to direct and reflected ultrasound, which was observed when the cleaning fluid was forced to circulate;

– at 60° and higher tilt angles, the lower part of the bearing receives less direct exposure to lateral radiation. This leads to a decrease in the quality and efficiency of cleaning.

A general view of the rolling bearing positioning setup, with adjustable angular orientation, is shown in Figure 2.

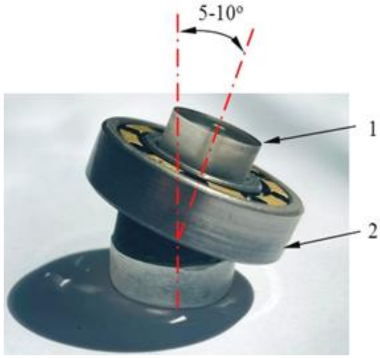


Figure 2 – External view of the rolling bearing positioning setup: 1 – bearing cradle; 2 – bearing

The cleaning process was carried out in a modified ultrasonic bath, which implements a combined ultrasonic and pulsed magnetic turbulent cleaning mechanism. A working fluid (i.e., aviation kerosene or water) heated to 30–40 °C generated turbulent flows for contaminant removal. Bearings were arranged in a circular configuration to ensure effective and uniform penetration of ultrasonic and electromagnetic fields. If necessary, bearings of many sizes and types can be cleaned using the system. A key advantage of this approach is the ability to clean miniature bearings in a single operation. A general view of the cleaning chamber (bath) with the installed ultrasonic emitters is shown in Figure 3.

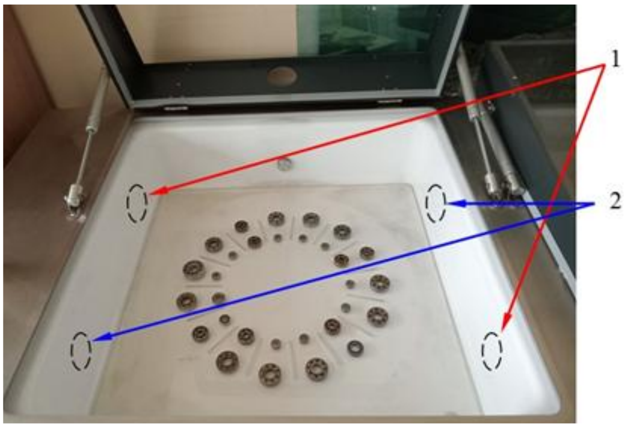


Figure 3 – General view of the ultrasonic cleaning bath with ultrasonic emitters mounted on the outer lateral surfaces of the bearing cleaning chamber: 1 – ultrasonic transducer with operating parameters of 8 kHz and 50 W; 2 – ultrasonic transducer with operating parameters of 40 kHz and 50 W.

The results of the study of the cleaning efficiency of miniature rolling bearings in the modernized ultrasonic bath are shown in Tables 1–2.

Table 1 – Comparative analysis of the cleaning efficiency of mini-ball bearings with the location of ultrasonic emitters at the bottom of the bath

Efficiency parameters	15°	30°	45°	60°
Direct impact of ultrasound	Minor on the top surface	Moderate on all surfaces	Moderate on all surfaces	Minor on the bottom surface
Cavitation availability	Limited to the top surface	Good on all surfaces	Good on all surfaces	Limited to the bottom surface
Contamination removal efficiency	Low on the upper surface	Medium to high	Medium to high	Low on the lower surface
Formation of shadow zones	On the lower surface	Minor	Minor	On the upper surface
Overall efficiency	Overall efficiency	Overall efficiency	Medium	Medium

Table 2 – Comparative analysis of the cleaning efficiency of mini-ball bearings with the location of ultrasonic emitters on the side walls of the bath

Efficiency parameters	15°	30°	45°	60°
Direct impact of ultrasound	Less on the upper surface	Balanced on all surfaces	Balanced on all surfaces	Less on the lower surface
Cavitation availability	Less on the upper surface	Good on all surfaces	Good on all surfaces	Less on the lower surface
Contamination removal efficiency	Less on the upper surface	Medium to high	Medium to high	Less on the lower surface
Formation of shadow zones	On a surface away from the emitter	Minor	Minor	On a surface away from the emitter
Overall efficiency	Medium	High	High	Medium

Thus, it has been experimentally determined that at the bottom and side locations of ultrasonic emitters, tilt angles in the range from 30° to 45° are the most effective for ensuring uniform cleaning. This arrangement provides a compromise between direct exposure and access of reflected waves from opposite walls and the bottom of the bath, reaching surfaces that are not directly aligned with the emitters and reducing the effect of shading some parts of the bearing structure elements by others. Therefore, in further studies, the bearings were placed on special mandrels tilted at angles from 30° to 45°.

Analysis of additional factors that influence the effectiveness of the results showed that an increase in the number and uniformity of the emitters leads to a more even distribution of energy, and higher power creates more intense cavitation. The actual cleaning efficiency may depend on many other factors, such as the power and frequency of the ultrasonic waves, the type and concentration of the cleaning solution, the complexity of the bearing design, the type and degree of contamination, and whether the liquid is rotated or agitated during the cleaning process.

4 Results

4.1 Analysis of contaminants

Contaminants are solid, liquid, and gaseous substances in the cavities of miniature rolling bearings and other tribological and mechanical systems that adversely affect their performance. The most common contaminants are metal particles (chips, metal dust from grinding and polishing, wear products), metal oxides, components of grinding and polishing pastes, residues of oils, solvents, fats, paint, dust and sand particles, corrosion and decomposition products of working and process fluids, microorganisms, and their waste products.

Essential properties of contaminants include their physical state and type of bonding with the surface, their tendency to polymerize, the presence of metal oxidation and corrosion products in a mixture with solid particles, their particle size distribution, and the presence of atmospheric dust. The mixture of solid pollutant particles, especially micro-, submicro-, and nano-sized ones, with solidified residues of fuels, lubricants, and working fluids is one of the most challenging problems. The removal of such contaminants from areas of small cross-sections and considerable length, gaps, crevices between cages and the rolling raceway, between raceways and rolling elements is complicated, which leads to the overlap, or so-called shadowing, of a significant part (from 30 % to 90 %, depending on the size) of the working surfaces by structural elements. As a result, due to the static position of the bearing, all its working surfaces cannot be cleaned to a high quality by most existing modern methods. This is especially true for miniature, precision, and special ball bearings.

Despite the peculiarities of the hydrodynamic flow, in particular cases, it can only move a particle of ferromagnetic contamination within the domains, which is insufficient for their final removal from the rolling path.

4.2 Design and study of the effectiveness of the method of finishing non-contact cleaning of rolling bearings

Modern methods of ultrasonic, cavitation, and pulsed hydraulic cleaning are not always effective enough due to the fundamental difference in the retention mechanism and the concept of removing magnetically susceptible contaminant microparticles.

Therefore, this paper presents an innovative method of cleaning the contacting surfaces of tribunals developed by the authors, based on the excitation and removal of micro- and submicro-ferromagnetic contaminant particles using ultrasound and pulsed electromagnetic fields [22, 23]. Such an impact effectively removes various microcontaminants from all available bearing surfaces, followed by their movement and retention in the maximum electromagnetic field intensity zone. Numerous successful implementations of this method and the developed devices for cleaning non-separable aircraft ball bearings of gas turbine engines at leading aircraft companies, such as JSC BMBP “PROGRESS”, “Motor Sich” JSC (Zaporizhzhia, Ukraine), and “Motor Repair Plant” (Lutsk, Ukraine), emphasize its significant practical importance.

Of the methods and modern equipment listed above, the most suitable for effective removal of contaminants from the working surfaces, parts and hidden areas of mini-ball bearings are Combining the pulsed magnetic turbulent method with the ultrasonic method of cleaning small and complex parts, such as high-precision mini-rolling bearings, allows cavitation to reach hard-to-reach places, enhance the effect of non-contact rotation and cleaning of bearings due to turbulent flows of cleaning fluid. Simultaneously, using a solvent (aviation kerosene) as a cleaning fluid will contribute to the effective removal of specific organic contaminants (oils and fats).

To implement the proposed cleaning method, a laboratory sample of a device with a source of combined action of pulsed alternating magnetic and ultrasonic fields was created (Figure 4).

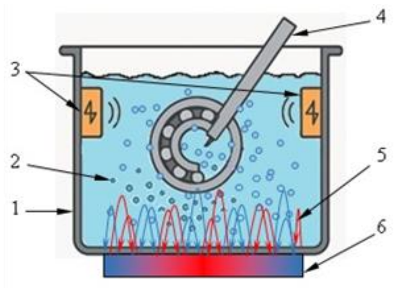
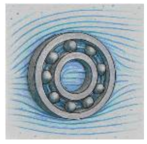
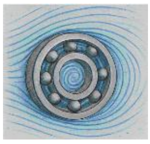
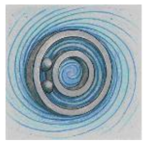


Figure 4 – Model of the device realizing the combination of pulsed-magnetic turbulence with the ultrasonic cleaning method: 1 – bath; 2 – cavitation in the cleaning liquid; 3 – side ultrasonic emitters; 4 – bearing position; 5 – pulsed magnetic alternating field; 6 - source of pulsed magnetic alternating field

The study of the process of pumping the cleaning fluid through the bearing, depending on the rotational speed, combining mechanics, hydrodynamic, and centrifugal effects, made it possible to determine the optimal and necessary operating parameters of the source of the pulsed magnetic alternating field (Table 3).

Table 3 – Comparative characteristics of the bearing cleaning

Parameter	Flow type and rotation speed		
	Laminar  10–50 rpm	Mixed*  ≥ 100 rpm	Turbulent  ≥ 500 rpm
Centrifugal force	Insignificant	Medium	High
Pumping liquids	Weak, passive	Active, stable	Intensive, with a risk of cavitation
Cooling effect	Minimal	Medium	High

* laminar & vortex.

Aviation kerosene was used as a cleaning medium. The cleaning time, depending on the degree of contamination and the type of bearing, ranges from several seconds to 2–3 minutes, which allows this method to be integrated into the technological cycle of rolling bearings manufacturing as a final cleaning operation, ensuring the principle of improving the innovation of production.

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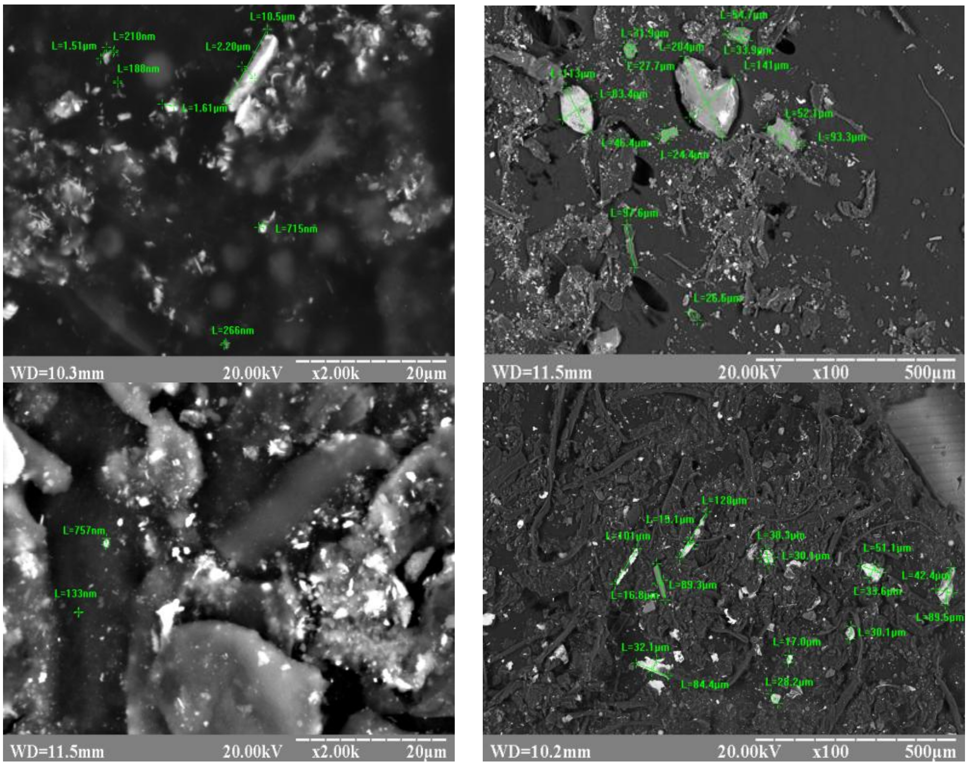
The cleaning fluid moves slowly between the balls and raceways at low rotational speeds under viscous friction. Simultaneously, there is no centrifugal force. Weak uniform flows were observed, where the main movement was due to the bearing geometry and natural convection. With increased rotation speed to 100 rpm, the centrifugal force began to act, squeezing the fluid from the center to the outer cage, and pronounced annular flows formed between the balls. Increasing the fluid pressure closer to the outer part of the bearing resulted in hydrodynamic lift and facilitated its rotation.

However, higher rotational speeds (≥ 500 rpm) led to an even greater increase and dominance of centrifugal forces, sharply squeezing the cleaning fluid outward and drawing fresh fluid inward. This forced, non-contact bearing rotation creates a pressure gradient in the liquid. The result is an increase in pressure in the outer areas where the centrifugal force pushes the fluid out and a decrease in pressure near the bearing, which also affects the movement of the washing liquid. The flow became intensely turbulent, where rarefaction zones and localized cavitation occurred, especially in the gaps between the balls and the cage.

The pressure distribution and the nature of the detergent flow in the gap between the rings are quite complex and are described by the equations of hydrodynamics, particularly the Reynolds equation for a thin layer.

This effect, defined in the adhesive hydrodynamic model of friction and wear, is the basis for developing a magnetic-turbulent method for cleaning ball bearings.

The basis of the developed method is a moving pulsed magnetic alternating field, which leads to the rotation of the outer cage of the ball bearing. At the same time, due to the magnetization of microparticles of ferromagnetic contaminants, it becomes possible to overcome magnetic fields at the boundaries of the domains with the subsequent removal of these particles into the flow of the cleaning fluid, which, due to the movement of the moving parts of the rolling bearing, has a turbulent flow. Studies of the effectiveness of the developed combined cleaning method on aircraft ball bearings have shown that the pulsed magnetic turbulent method allows more efficient removal of contaminant particles whose size is much larger than 1–2 μm (Figure 5), while the average value of the total noise level of bearings decreased by 2.2–8.0 dB.



a b

Figure 5 – Measurements of the average size and number of removed contaminant particles on the scanning electron microscope REM-106I: a – after cleaning by the ultrasonic method; b – cleaning by the pulsed magnetic turbulent method

Using the ultrasonic method alone reduced the overall noise level of bearings in the 1.0–2.5 dB range. However, using ultrasound allows for the most effective removal of the smallest micro-, submicro-, and nanoparticles of contaminants (≤1 μm in size).

The study showed that the most contaminant particles recorded on the filter elements were up to 5 μm in size, while larger particles over 50 μm were observed much less frequently.

The smallest particles with a size of less than 1 μm were recorded (Figure 6).

The study of the chemical composition of contaminants (Figure 7) showed that most of them are metal ferromagnetic fragments in the form of metal particles and chips.

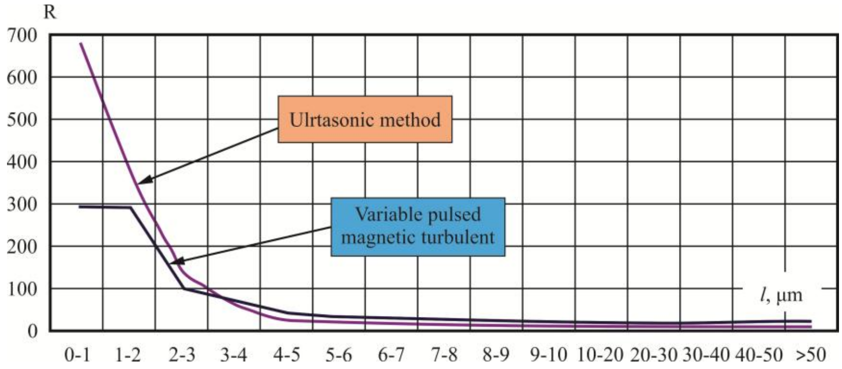


Figure 6 – The dependence of the determined relative amount of contaminants *R* on their average linear size *l* after two-stage cleaning: 1 – the first stage by the pulsed magnetic turbulent method; 2 – the use of ultrasonic cleaning, after the first stage

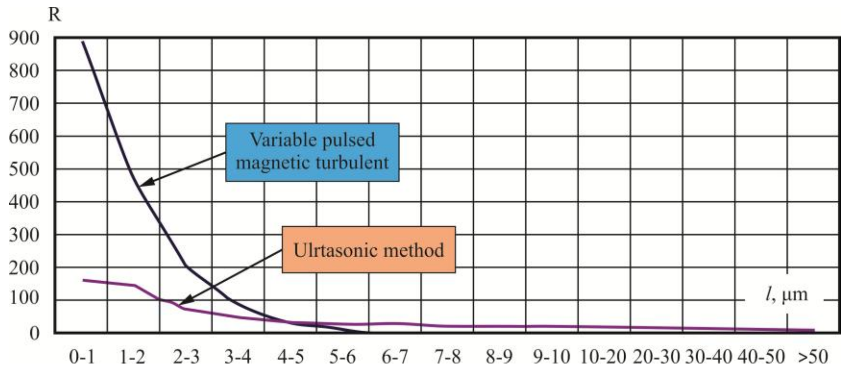


Figure 7 – The dependence of the determined relative amount of contaminants *R* on their average linear size *l* after two-stage cleaning: 1 – the first stage by ultrasonic method; 2 – using the pulsed magnetic turbulent cleaning method, after the ultrasonic method

5 Discussion

The obtained results reveal a clear trend indicating that, due to non-contact rotation, every point on the surface of the tested miniature ball bearings periodically enters the zone of direct exposure to the pulsed alternating magnetic field and ultrasonic waves, regardless of the inclination angle.

During the cleaning process, a more uniform distribution of cavitation bubbles over the entire ball bearing surface is ensured and their penetration into hard-to-reach places is facilitated, almost eliminating the problem of shadow zones and significantly increasing the efficiency of contaminant removal.

Non-contact rotation is key to achieving high cleaning efficiency at any ball-bearing inclination angle. However, for mini- and precision bearings of small dimensions (e.g., diameter less than 10 mm), the angle of inclination can play a more significant role in ensuring access of ultrasonic waves and pulsed magnetic alternating fields to small parts. Therefore, angles from 30° to 45° remain optimal for the best results.

For larger bearings, with an outer diameter of 10 mm to 30 mm, the influence of the angle of inclination can be less critical, due to the larger volume of liquid and the possibilities of wave propagation. However, in this case, ensuring uniform rotation and sufficient power of the combined ultrasonic source and pulsed magnetic alternating field comes to the fore.

The results of vibro-diagnostics obtained before and after using the developed cleaning method, compared with the results of repeated tests, showed a significant improvement in the operational characteristics of the studied aircraft bearings. A substantial decrease in the vibration level was observed on average by 7–25 %, and in some bearings, this indicator decreased by 35–45 %. The results obtained confirm the high efficiency of the developed method.

6 Conclusions

Based on the analysis of modern existing cleaning methods, comprehensive theoretical and experimental research, a new method for contactless removal of micro- and sub-microparticles of contaminants from the working friction surfaces of miniature ball bearings has been created, which is an urgent task for ensuring their reliable and durable operation in high-tech industries.

It has been experimentally established that ultrasonic cleaning is one of the most common and effective methods for precision parts, but it has limitations associated with a static position, leading to surface shielding. It has also been determined that when using a standard ultrasonic bath, the bearings' most effective inclination angles lie from 30° to 45°. Modernizing the standard bath with side emitters changed the nature of the distribution of ultrasonic waves and the influence of the inclination angle on the efficiency of cleaning the ball bearing.

For the first time, the mechanism of retention of ferromagnetic microparticles on the working surfaces of ferromagnetic parts by magnetic fields of domain boundaries has been identified. A comparative analysis of the cleaning efficiency of aircraft ball bearings has shown that the pulse-magnetic turbulent method is more effective for removing particles larger than 1–2 μm, while the ultrasonic method copes better with smaller contaminants (≤1 μm).

Considering the mechanism of retention of ferromagnetic microparticles on the surface of ferromagnetic parts by magnetic fields of domain boundaries and the elimination of shielding of hidden surfaces of ball bearing parts, a laboratory sample of a cleaning device was developed that uses the combined action of variable pulsed magnetic and ultrasonic fields and ensures a constant change in the orientation of the bearing and a uniform effect on all its surfaces, significantly increasing the efficiency of contamination removal regardless of the angle of inclination.

To further improve the sample device with a combined source of variable pulsed magnetic and ultrasonic fields, studies were conducted on the dependence of the effect of the washing fluid pumping process on the bearing rotation speed, which made it possible to determine the optimal operating parameters of the source of the variable pulsed magnetic turbulent field.

Thus, the innovative method of non-contact cleaning, using variable pulsed magnetic, turbulent, and ultrasonic fields, is a promising solution for the high-quality cleaning of miniature and precision ball bearings, especially in high cleanliness requirements in the aviation and defense industries.

Further research will aim to optimize the parameters of the combined effect of the fields and expand the scope of the developed method.

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